Draft version August 14, 2008
Preprint typeset using LaTeX style emulateapj v. 03/07/07

THE EFFECT OF A STELLAR MAGNETIC VARIATION ON THE JET VELOCITY

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Draft version August 14, 2008

ABSTRACT

Stellar jets are normally constituted by chains of knots with some periodicity in their spatial distribution, corresponding to a variability of order of several years in the ejection from the protostar/disk system. A widely accepted theory for the presence of knots is related to the generation of internal working surfaces due to variations in the jet ejection velocity. In this paper we study the effect of variations in the inner disk-wind radius on the jet ejection velocity. We show that a small variation in the inner disk-wind radius produce a variation in the jet velocity large enough to generate the observed knots. We also show that the variation in the inner radius may be related to a variation of the stellar magnetic field.

Subject headings: accretion, accretion disks – ISM: Herbig-Haro objects – ISM: jets and outflows – stars: magnetic fields – stars: pre-main sequence – winds, outflows.

1. INTRODUCTION

Stellar jets are observed in the form of chains of emitting nebulae called Herbig-Haro (HH) objects. HH objects are generally thought to be shock-heated density condensations traveling along the outflows formed by star-disk systems during the process of star formation (e.g. Reipurth & Bally 2001).

Since their discovery several scenarios have been suggested for the origin of *steady* outflows from young stellar objects. In the stellar wind model, material is accelerated by thermal pressure gradients (e.g. Cantó 1980). Magnetohydrodynamics (MHD) models rely on the magnetocentrifugal launching mechanism (Blandford & Payne 1982). For the X-wind scenario the jet is magnetically driven from the so-called "X-annulus" where the young star's magnetosphere interacts with the disk (Shu et al. 2000). In the disk wind scenario the jet is launched from an extended region of the disk surface (e.g. Ferreira 1997). The analytical models mentioned above have focused mainly on the steady-state aspect of the ejection phenomena.

Unsteady periodic ejections with timescales of the order of several rotation periods of the inner disk radius have been obtained by numerical simulations (e.g. Ouyed & Pudritz 1997; Goodson & Winglee 1999; Matt et al. 2002). Observations indicate a significantly longer timescale is associated with the appearance of knots in stellar outflows. Nearly all observed jets present small scale knots up to 0.1 pc from the central source, with a spacing between the knots corresponding to a timescale of $\approx$ 1-20 yr (e.g. HH30 - Burrows et al. 1996; HH111 - Reipurth et al. 1992; RW-Aur - López-Martín et al. 2003). More fragmented knots are observed on a typical timescale of $\sim 10^{2-3}$ yr at larger distances from the source. While the long term variation of jets can be explained by variations in the accretion rates (e.g. during FU-Orionis phases), the possible origin of small scale knots is still unclear.

A first possibility, suggested by similarities with extragalactic jets, is that the knots may be formed by hydrodynamics Kelvin-Helmholtz instabilities (Micono et al. 1998), MHD Kelvin-Helmholtz reflective pinch mode instabilities (Cerqueira & de Gouveia Dal Pino 1999), or by current-driven instabilities (Frank et al. 2000). Numerical simulations by these authors have shown that the shocks generated by plasma instabilities are weaker than those seen in observations once radiative cooling is taken into account. Moreover, some jets (e.g. HH212 - Zinnecker et al. 1998) show a remarkable symmetry on both sides of the central star-disk system. This may be difficult to explain assuming that the instabilities are triggered by small scale perturbations. Additionally, and more importantly, optical images in many cases show that the compact knots have a bow-shock structure (e.g. HH111 - Reipurth et al. 1992) that is difficult to obtain supposing that the knots are formed by instabilities.

A widely accepted theory for the presence of knots in stellar jets is related to the generation of internal working surfaces due to supersonic variations of the ejection velocity at the base of the jet (Raga et al. 1990). Indeed, numerical simulations, using a velocity variations of about 10-20% of the average velocity, have been able to reproduce the morphology and the emission property of the knots in HH objects (e.g. Esquivel et al. 2007).

In this paper we show that velocity variations which lead to the creation of knots similar to the observed ones may be generated by variations of the inner disk-wind radius. Furthermore, we suggest that these variations may be related to changes in the stellar magnetic field.

This paper is organized as follows. In Section 2 we determine the effect of a variation in the inner disk radius on the jet velocity. In Section 3 we suggest that the variation in the inner radius could be connected to a change of the stellar magnetic field. In Section 4 we discuss the approximation used and the limitations of our model. Conclusions are given in Section 5.

2. THE EFFECT OF A VARIABLE INNER EJECTION RADIUS ON THE JET VELOCITY

We first discuss some asymptotic properties of a single fieldline anchored to an accretion disk as a function of the conserved invariants and the fieldline's footpoint radius. Then we extend the discussion to an ensemble of fieldlines anchored at a range of footpoint radii and derive mean values for the asymptotic velocity of a disk-wind extending from an inner to an outer finite radius. Lastly, we discuss the consequences of a time-dependent inner disk-wind radius on the average velocity of the outflow.

2.1. *Asymptotics along a single fieldline*

In steady state, axisymmetric, ideal MHD a number of quantities are conserved along a fieldline, i. e. a surface of constant magnetic flux Ψ. Among these invariants are the mass-to-magnetic flux ratio $k(\Psi)$, the total angular momentum $L(\Psi)$ and the corotation frequency or angular velocity $\Omega(\Psi)$ (e.g. Blandford & Payne 1982; Pelletier & Pudritz 1992). These invariants are defined as

$$k(\Psi) = 4\pi\rho\,\frac{V_{\rm p}}{B_{\rm p}}\,, \tag{1}$$

$$L(\Psi) = R\left(V_\phi - \frac{B_\phi}{k(\Psi)}\right)\,, \tag{2}$$

$$\Omega(\Psi) = \frac{1}{R}\left(V_\phi - \frac{k(\Psi)}{4\pi\rho}B_\phi\right)\,, \tag{3}$$

where ρ is the mass density, $V_{\rm p}$, V_ϕ, $B_{\rm p}$, B_ϕ are the poloidal and toroidal components of the velocity and magnetic field, and R is the distance from the star. The invariants $k(\Psi)$, $\Omega(\Psi)$, $L(\Psi)$ and the footpoint $R_0(\Psi)$ are assumed to be known or given functions.

$L(\Psi)$ includes contributions from the twisted magnetic field. The relation

$$L(\Psi) = R_{\rm A}^2(\Psi)\,\Omega(\Psi) \tag{4}$$

holds, where $R_{\rm A}(\Psi)$ is the Alfvén radius. Eq. (4) determines $R_{\rm A}(\Psi)$ and subsequently $\lambda(\Psi) = R_{\rm A}(\Psi)/R_0(\Psi)$ (the magnetic lever arm) completely. Here, and in the following, all quantities with an explicitly indicated functional dependency on Ψ, e.g. $L(\Psi)$, are taken to depend on the magnetic flux Ψ only. Similarly, all quantities with a subscript $_0$ are taken to be defined at the base of the fieldline, i. e. the equatorial plane. The corotation frequency $\Omega(\Psi)$ can be easily evaluated at the equator – where the poloidal velocity component $V_{\rm p}$ vanishes – and equals the orbital frequency at the equatorial plane Ω_0:

$$\Omega(\Psi) = \Omega_0(\Psi)\,. \tag{5}$$

Another conserved quantity is given by the total energy $E(\Psi)$ per unit mass, with contributions from kinetic, thermal, gravitational energy Φ and the energy of the electromagnetic field (Poynting flux):

$$E(\Psi) = \frac{1}{2}V^2 + \frac{\gamma}{\gamma-1}\frac{P}{\rho} + \Phi - \frac{\Omega(\Psi)RB_\phi}{k(\Psi)}\,, \tag{6}$$

where P is the thermal pressure and γ is the ratio of specific heats. The asymptotic jet velocity along a fieldline Ψ anchored at the footpoint radius $R_0(\Psi)$ can be estimated from the Bernoulli equation for large distances and negligible enthalpy as (Michel 1969):

$$v_\infty(\Psi) \sim \sqrt{2}\,\Omega(\Psi)\,R_0(\Psi)\,\lambda(\Psi)\,. \tag{7}$$

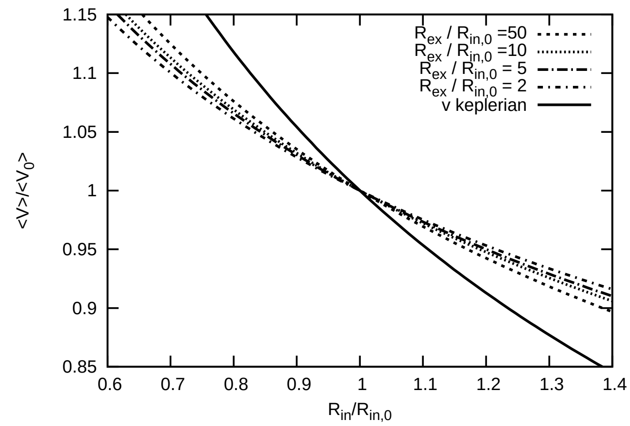

FIG. 1.— Average outflow velocity as a function of $R_{\rm in}/R_{\rm in,0}$. The average outflow velocity is normalized to $\langle v_0\rangle = \langle v\rangle_{R=R_{\rm in,0}}$.

The asymptotic jet velocity varies from fieldline to fieldline. However, we are ultimately interested in a typical value representative of the jet as a whole. Therefore, we will weigh the asymptotic velocity with the mass-flux carried by the fieldline.

The asymptotic mass-flux along a fieldline per unit magnetic flux (for one hemisphere) can be estimated by rewriting eq. (1) as

$$\frac{\partial \dot{M}}{\partial \Psi} = \frac{k(\Psi)}{2}\,, \tag{8}$$

where $\dot{M}$ is the wind mass-loss rate.

2.2. *Asymptotic mean jet velocity*

The jet is assumed to originate in a disk-wind. Mass loading onto the disk-wind shall be efficient only for magnetic flux surfaces in the range $\Psi_{\rm in} \le \Psi \le \Psi_{\rm ex}$, where the flux surfaces $\Psi_{\rm in}$ and $\Psi_{\rm ex}$ are anchored at $R_{\rm in} = R_0(\Psi_{\rm in})$ and $R_{\rm ex} = R_0(\Psi_{\rm ex})$, respectively. The mean or typical velocity of the jet given by the superposition of the asymptotic velocities along the fieldlines anchored between $R_{\rm in}$ and $R_{\rm ex}$ can be determined weighting the jet velocity by the mass-flux carried along every fieldline:

$$\langle v\rangle = \frac{\int_{R_{\rm in}}^{R_{\rm ex}} v_\infty d\dot{M}}{\int_{R_{\rm in}}^{R_{\rm ex}} d\dot{M}}\,. \tag{9}$$

So far, we have assumed steady state and axisymmetry. In the following we will add two assumptions, namely keplerian rotation and self-similarity (see e.g. Vlahakis & Tsinganos 1998).

Assuming keplerian rotation for the plasma in the equatorial plane fixes the corotation frequency to

$$\Omega(\Psi) = \Omega_0(R_0(\Psi)) = \sqrt{\frac{GM}{R_0^3(\Psi)}}\,. \tag{10}$$

The magnetic flux is a power-law in Ω, i. e. $\Psi \sim \Omega^{-\alpha}$. Self-similarity fixes the power-law index to $\alpha = 1/2$ (Blandford & Payne 1982). In terms of the footpoint radius R_0, Ψ is given by

$$\Psi = \Psi_{\rm ex}\,(R_0/R_{\rm ex})^{3/4}\,. \tag{11}$$

Self-similarity also fixes the mass-to-magnetic flux function $k(\Psi)$ to

$$k(\Psi) = k_{\rm ex}\,(R_0/R_{\rm ex})^{-3/4}\,, \tag{12}$$

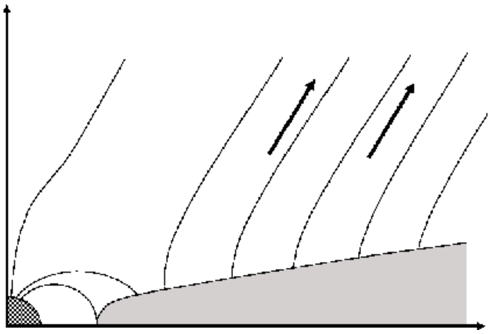

FIG. 2.— Schematic representation of the studied model, where an extended disk-wind is ejected by an accretion disk with a time-varying stellar magnetic field.

and renders the lever arm independent of the magnetic flux surface (i. e. $\lambda(\Psi) = \lambda$). Keplerian rotation and constant λ is sufficient to completely determine the asymptotic velocity along a fieldline as

$$v_\infty(\Psi) = \lambda \sqrt{\frac{2GM}{R_0(\Psi)}}\,, \tag{13}$$

while the wind mass-loss rate is determined by eq. 8 and yields

$$d\dot{M} = \frac{3}{8} k_{\rm ex} \Psi_{\rm ex} \frac{dR_0}{R_0}\,. \tag{14}$$

Finally, defining $\chi = R_{\rm ex}/R_{\rm in}$, the average velocity (eq. 9) can be integrated, giving:

$$\langle v \rangle = 2\,\frac{\chi^{1/2} - 1}{\ln \chi}\, v_\infty(R_{\rm ex})\,. \tag{15}$$

where $R_{\rm ex}$ is assumed fixed. The velocity variation as function of the inner radius, for different values of χ, is shown in Fig. 1. As this Figure clearly shows, an increase in the inner radius causes a decrease in the average velocity. Moreover, the velocity variation is nearly independent of the ratio $\chi_0 = R_{\rm ex}/R_{\rm in,0}$ (where $R_{\rm in,0}$ is a position of the inner radius chosen as a reference). To produce a variation of 20% in velocity it is necessary to have a variation of order of 30% in the inner radius. Fig. 1 shows also the difference between the velocity of the disk-wind at the inner radius (keplerian, see eq. 13) and the average velocity (defined by eq. 9).

3. THE EFFECT OF A MAGNETIC FIELD CYCLE ON THE INNER DISK-WIND RADIUS

So far, we have dealt exclusively with the magnetic field of the disk-wind. These magnetic flux surfaces carrying the disk-wind are necessarily open to infinity. A non-open fieldline cannot contribute to the global outflow. In the following we consider the superposition of a dipolar magnetosphere carried by the central star, contributing magnetic flux $\Psi_{\rm DP}$ and the previously discussed magnetic field Ψ which threads the disk and carries the outflow. Then the total magnetic flux is given by $\Psi + \Psi_{\rm DP}$.

This configuration leads to three different kinds of magnetic field lines as is illustrated in Fig. 2. Firstly, fieldlines anchored in the polar region of the stellar surface. While these fieldlines are open to infinity, they are assumed to carry only negligible mass-flux and do not contribute significantly to the outflow. Secondly, closed dipolar fieldlines anchored at lower latitudes of the stellar surface do not contribute to the outflow in our model.

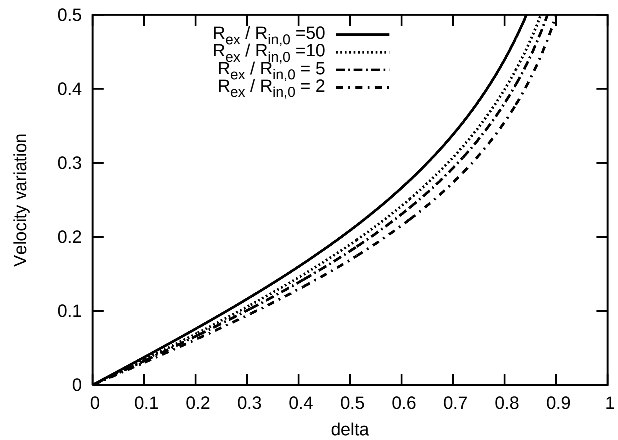

FIG. 3.— Variation of the velocity (normalized to the average velocity) as a function of δ (the amplitude of the stellar magnetic field variation) for different values of χ_0.

Lastly, a global open magnetic field threading the disk, which carries the disk-wind.

The transition from the closed dipolar fieldlines to the open disk-wind, i. e. the location of the innermost open flux surface $\Psi_{\rm in}$ in the equatorial plane, is given by the location of the saddle point of the magnetic flux distribution

$$\left[\frac{d}{dR_0}\left(\Psi + \Psi_{\rm DP}\right)\right]_{R_0 = R_{\rm in}} = 0\,, \tag{16}$$

where the dipolar field on the equatorial plane is given by a time-varying dipole moment $m(t)$ as

$$\Psi_{\rm DP} \propto m(t) \frac{1}{R_0}. \tag{17}$$

and Ψ is given by eq. 11. Since both magnetic flux distributions are known, the inner radius of the disk-wind is given in terms of the time-varying stellar magnetic field (defined on the stellar surface) from eq. 16 as

$$R_{\rm in} \propto |m(t)|^{4/7}. \tag{18}$$

For simplicity, the stellar magnetic dipole moment is assumed to vary in time as

$$m(t) = m_0\left(1 + \delta\, \sin(2\pi t/\tau_\star)\right) \tag{19}$$

where $\tau_\star$ and δ are the period and the amplitude of the stellar magnetic field variation, and m_0 is the stellar magnetic dipole moment at $t = 0$.

The inner radius of the ejecting region depends on the variation in the magnetic field intensity, and changes on timescales of $\tau_\star$. The average velocity will therefore change periodically following the magnetic field cyclic variation.

A plot of the velocity variations, that is the difference between the maximum and minimum velocity, and normalized to the average velocity during one cycle of the stellar magnetic field, is shown in Fig. 3 as function of δ. The different curves are calculated corresponding to different values of χ_0 ($= R_{\rm ex}/R_{\rm in,0}$). A 50% variation in the stellar magnetic field produces a $\sim$ 20% jet velocity variation, nearly independent of the value of χ_0.

We have assumed that the only effect of a stellar magnetic field variation on the ejected jet is a change in $R_{\rm in}$. Actually, some of the open stellar flux will thread the

disk. Therefore, the disk magnetic field (including also the contribution from the open stellar magnetic flux) will not decrease as $\sim R_0^{-5/4}$ and will also change with time following the change in the stellar dipole.

A change in the stellar magnetic field produces changes in the mass-flux and velocity. In fact, the lever arm λ is a function of the magnetic field and of the mass flux (that is also a function of the magnetic field). Ferreira (1997) and Casse & Ferreira (2000) studied models of self-similar MHD accretion disks driving jets. These authors showed that $\lambda^2 \sim 1+1/(2\xi)$, where ξ is the ejection parameter (that relates the mass flux to the radius by $\dot{M} \sim r^{\xi}$). Additionally, $\xi \sim 0.1\mu^3$, where μ is the magnetization parameter (given by $\mu = B^2/(8\pi p)$, where p is the thermal pressure).

In this case, eq. 13 and 14 may be written as:

$$v_\infty(\Psi) = \lambda(\Psi)\sqrt{\frac{2GM}{R_0(\Psi)}}\,, \qquad d\dot{M} \propto \xi\, R_0^{\xi}\,\frac{dR_0}{R_0} \tag{20}$$

An increase of the magnetic field in the disk (due to the increased stellar contribution) produces an increase in the ejection parameter ξ and of the mass flux, and a drop in the asymptotic velocity. Therefore, the jet velocity decreases further with respect to the value calculated by eq. 15.

The average velocity (eq. 9) is given by:

$$\langle v\rangle = \frac{\int_{1/\chi}^{1} v_\infty(R_{\rm ex})\lambda/\lambda(R_{\rm ex})\xi x^{\xi-3/2}dx}{\int_{1/\chi}^{1}\xi x^{\xi-1}dx}\,. \tag{21}$$

where in the integrals $x = R_0/R_{\rm ex}$. Assuming ξ independent of x (i. e. self-similarity), eq. 21 leads to:

$$\langle v\rangle = 2\,\frac{\xi}{1-2\xi}\,\frac{\chi^{1/2}-\chi^{\xi}}{\chi^{\xi}-1}\,v_\infty(R_{\rm ex})\,, \tag{22}$$

where $R_{\rm ex}$ is assumed to be fixed, but $v_\infty(R_{\rm ex})$ varies with the stellar magnetic field as a function of $\lambda(R_{\rm ex})$ ($\sim 1/(2\xi)^{1/2}$ for $\xi \ll 1$).

For $\xi \to 0$ (assuming that λ is converging to a large but finite value) eq. 22 reduces to eq. 15.

The ratio between the external and inner radius χ is difficult to determine theoretically, but has been recently constrained by observations. In fact, interpreting the observed transverse velocity shifts in T Tauri microjets as indication of rotation, a range of ejecting radii corresponding to $\chi \approx 10$ can be inferred (e.g. Ferreira et al. 2006).

Therefore, we may assume $\xi \ll 1$, and write the average outflow velocity normalized to $\langle v_0\rangle = \langle v\rangle_{R=R_{\rm in,0}}$ as:

$$\frac{\langle v\rangle}{\langle v_0\rangle} \approx \left(\frac{\langle v\rangle}{\langle v_0\rangle}\right)_{\xi=0}\sqrt{\frac{\xi_0}{\xi}} \tag{23}$$

where the scaling $\langle v\rangle \sim 1/\sqrt{\xi}$ comes directly from $v_\infty \sim \lambda \sim 1/\sqrt{\xi}$. From this equation, it becomes clear that the stellar magnetic field variation necessary to produce a 20% variation in the average velocity may be much smaller than the 50% value determined from Fig. 3. The 50% value represents an upper limit to the necessary stellar magnetic field variation.

4. DISCUSSION

Is this section we discuss in some detail the approximations and the limitations of the model. First, to use the results from the standard disk-wind theory, we approximated the evolution of the system as a sequence of steady-state configurations.

We made two key assumptions on the behavior of the stellar magnetic field. The first assumption of a dipolar stellar magnetic field at the inner edge of the disk is standard in the magnetospheric accretion model for young stars (Königl 1991). On the stellar surface, magnetic fields as large as several kG have been observed (e.g. Johns-Krull 1997). The dipole component ($\sim 100-500$ G on the stellar surface), which decays more slowly then the multipole components, dominates at large distances from the star.

The second hypothesis is that a dynamo mechanism operates in protostars (Chabrier & Küker 2006; Dobler et al. 2006) with a periodic or quasi-periodic variation of the magnetic field with a typical timescale of a few to tens of years. A dynamo mechanism is necessary to explain the observed magnetic field, because this would be dissipated on scales of order of $R_\star/\eta \approx 100$ yr, where $R_\star$ is the stellar radius and η is the turbulent magnetic diffusivity (e.g. Chabrier & Küker 2006). A dynamo mechanism, if present, is not necessarily cyclic as needed by our model. However, recently Sokoloff et al. (2008) proposed models of dynamos in low mass, fully convective stars with a cyclic magnetic field. The photometric variability observed in T Tauri stars (e.g. Mel'Nikov & Grankin 2005; Grankin et al. 2007) may be related to a corresponding change in the stellar magnetic field (Armitage 1995).

Finally, our results depend on the complex interaction between the stellar magnetic field and the disk. This has been studied by a number of authors both analytically and numerically (see, e.g., Uzdensky 2004 and references therein). It is well understood that the differential rotation in the disk produces a winding-up of the magnetic field lines on a timescale $\tau = 2\pi/(\Omega_\star - \Omega)$ (where $\Omega_\star$ is the stellar rotation frequency) with a following opening of the stellar magnetic field lines and a consequent outflow.

The later evolution of the system is unclear. Once the magnetic field lines are opened, they can stay in that configuration indefinitely (Lovelace et al. 1995) allowing a disk-wind to be ejected from an inner radius $R_{\rm in}$ to an outer radius $R_{\rm ex}$. In this case the stellar magnetic field lines are connected to the disk only in a small region around $R_{\rm in}$ (see Fig. 2). $R_{\rm in}$ can be determined as the distance from the star where the magnetic stress $B_\phi B_p R_0^2$ begin to dominates over the viscous stress $\dot{M}d\left(\Omega R_0^2\right)/dR_0$ (e.g. Wang 1996):

$$R_{\rm in} = B_p(t)^{4/7}\left[\frac{2R_\star^6}{\dot{M}\,(GM_\star)^{1/2}}\right]^{2/7} \tag{24}$$

where $R_\star$ and $M_\star$ are the star radius and mass, $\Omega = (GM/R_0^3)^{1/2}$, and we assume $B_\phi \approx B_p$ (with $B_p \propto m$, defined by eq. 19) and a full penetration of the vertical magnetic field lines into the disk. The same dependence of $R_{\rm in}$ on B_p is recovered and the results obtained in the previous section are unchanged.

Alternatively the stellar-disk magnetic field lines might close again via magnetic reconnection producing quasi-periodic ejections (e.g. Goodson & Winglee 1999; Matt et al. 2002). Our results correspond to the hypothesis that the mass flux carried by the quasi-periodic ejections is much less then the mass flux carried by the disk-wind. If on the other side the mass flux carried by the coronal mass ejection is important, the stellar cycle would also produce a variation in the jet velocity. Actually, in contrast with the disk-wind case, for a coronal mass ejection an increase in the magnetic field would produce an increase in the ejection velocity (as found in simulations by Matt et al. 2002). In fact, in coronal mass ejections the magnetic energy is directly transformed in kinetic energy by reconnection events.

We concentrated on a cyclic magnetic field as origin of the variations in the inner launching radius for the disk wind. However, any physical process that leads to quasi-periodic variations of the launching region will result in similar variations of the mean asymptotic velocity – and therefore to the appearance of knots – as long as those variations are large enough.

It is unclear which process (other than a stellar magnetic field variation) might create variations on a $\sim 1-20$ yr timescale. Spruit & Taam (1993) showed that a relaxation oscillator may produce a change in the inner radius in X-ray binaries. The timescale of the oscillation depends on the details of the stellar magnetosphere and can vary by two orders of magnitude. A variation in the accretion rate may also produce a similar variation in the inner radius (see eq. 24, and the discussion by Blackman et al. 2001).

Hartigan et al. (2004) showed that short period T Tauri binaries do not seem to have jet properties different from those of wider binaries or single stars, arguing in this way against binarity as the origin of jet knots. Hartigan et al. (2004) also argued that there is no correlation between the ejection of a new knot in CW Tau and an increase in source brightness. One might have expected this if the knot was caused by an accretion outburst. Finally, Ferreira et al. (2006) suggested that the alternation between X- and Y-type interactions between stellar and disk magnetic fields as due to a magnetic field cycle could explain the observed periodicity.

5. CONCLUSIONS

In this paper we explored the effect of a stellar magnetic field variation on the ejection velocity of protostellar jets. While large scale knots may successfully be explained by a large increase in the accretion rate, we showed that small scale knots may be produced by changes in the inner radius.

We showed that a stellar magnetic field variation, if present, represents a natural candidate to produce stellar knots similar to the observed. In fact, a stellar magnetic field variation produces a change in the inner radius and therefore in the jet velocity. We also estimated that a stellar magnetic field variation $\lesssim 50\%$ produces a variation ($\sim 20\%$) in the average velocity large enough to produce knots similar to the observed.

The stellar magnetic field periodic or quasi-periodic variation remains an hypothesis of our scenario, but future large scale temporal observations of magnetic field in young stars, and progress in dynamo theory, will both help to provide an answer to this problem.

We thank Turlough Downes, Jonathan Ferreira, Tom Ray and Nektarios Vlahakis for useful discussions. We also acknowledge Edith Salado Lopez for the elaboration of Fig. 2. Part of this work was supported by the European Community's Marie Curie Actions - Human Resource and Mobility within the JETSET (Jet Simulations, Experiments and Theory) network under contract MRTN-CT-2004 005592, and by the Agence Nationale de la Recherche (ANR).

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